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Crop residue effects on soil quality following 10-years of no-till corn[1]

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Abstract

Numerous biological, chemical, and physical indicators of soil quality have been suggested, but few have been evaluated using data from long-term field studies. Our objective was to evaluate several proposed soil quality indicators to determine effects of removing, doubling, or maintaining crop residues for 10 years in a no-till, continuous corn (*Zea mays* L.) production study. Soil aggregate characteristics, penetration resistance, bulk density, volumetric water content, earthworm populations, respiration, microbial biomass, ergosterol concentrations, and several soil-test parameters (pH, P, K, Ca, Mg, Total-N, Total-C, NH_4-N, and NO_3-N) were measured on samples collected from Rozetta and Palsgrove silt loam (fine-silty, mixed, mesic Typic Hapludalfs) soils. Soil aggregates from double residue treatments were more stable in water than those from normal and removal treatments. The double and normal residue treatments had higher total carbon concentrations and higher levels of microbial activity as measured by CO_2 evolution. Ergosterol concentrations where crop residues were removed were 8 to 10 times lower suggesting this biochemical measurement of fungal biomass may be a sensitive soil quality indicator. Earthworm populations where crop residues had been removed for 10 years were significantly lower than in either normal or double residue treatments. Measures of force and energy required to crush soil aggregates were extremely variable and showed significant differences only for aggregate size. Several parameters were used to develop a soil quality index that gave ratings of 0.45, 0.68, or 0.86 for removal, normal, or double residue treatments,

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respectively. This study demonstrates a framework for soil quality evaluation and shows how crop residue management can affect this rating.

Keywords: Crop residue management; Soil quality index; No-tillage

1. Introduction

Crop residue management practices have been included in many United States Department of Agriculture (USDA) Soil Conservation Service (SCS) farm plans, because those practices can reduce soil erosion, runoff, and off-site sedimentation. Reduced labor and machinery costs are economic considerations that are frequently given as additional reasons to use crop residue management practices. Our perception is that soil quality will also be improved by adoption of crop residue management practices. To test this hypothesis, long-term effects on soil biological, chemical, and physical properties need to be documented.

The concept of soil quality has been suggested by several authors (Lal, 1991; Sanders, 1992; Granatstein and Bezdicek, 1992; Papendick and Parr, 1992; Parr et al., 1992; Karlen et al., 1992; Acton and Padbury, 1993) as a tool for assessing long-term sustainability of agricultural practices at local, regional, national, and international levels. We attempted to evaluate soil quality by sampling long-term crop residue management treatments and documenting biological, chemical, and physical differences as a 10-year, no-tillage corn production study was being terminated.

Our evaluation was conducted on a long-term no-till site established on loess-derived Rozetta and Palsgrove soils. These soils are representative of those that form mantles over fractured shale, sandstone, and limestone bedrock and extend across the Upper Mississippi Valley of NW Illinois, SW Wisconsin, SE Minnesota and NE Iowa in the United States. This area is often referred to as being the "driftless" region because the landscape and soils were apparently not modified by recent glaciation. The topography is characterized by steep slopes, varied slope aspects, bluffs, rock outcrops, sinkholes, springs, and entrenched stream valleys. Soils in this region are generally highly productive, but erosion is a serious threat to long-term cropland productivity.

1.1. Potential soil quality indicators

A soil quality attribute (indicator) is a measurable soil property that influences the capacity of a soil to perform a specified function (Acton and Padbury, 1993). Several indicators have been suggested reflecting changes over various spatial and temporal scales. Soil depth, soil organic matter, and electrical conductivity were selected by Arshad and Coen (1992) as properties most affected by soil degradation processes. For evaluation of soil quality, selection of indicators that are sensitive to management practices is desirable.

Several biological attributes, including microbial biomass, respiration, amino acids, soil enzymes, and earthworm activity have been suggested as soil quality indicators. Physical conditions, including water-filled pore space which influences biological activity, have also been identified as important indicators. Although water-filled pore space and many of the biological indicators are much more temporally, and perhaps spatially, dependent than physical indicators such as bulk density or chemical indicators such as cation exchange capacity (CEC), they can be very responsive to soil and crop management practices (Linn and Doran, 1984a, 1984b; Doran et al., 1990).

Aggregate stability and size distribution are two physical measurements suggested as indicators for evaluating effects of soil and crop management practices on soil quality (Arshad and Coen, 1992). These measurements were suggested because they reflect resistance of soil to erosion (Luk, 1979). Soil dispersion in water has also been related to erosion and runoff (Miller and Baharuddin, 1986; Stern et al., 1991). Soil carbon content has been suggested as a soil quality indicator because decreases in this parameter can be directly related to decreased water stability of both macro- and micro-aggregates (Tisdall and Oades, 1982; Churchman and Tate, 1987; Pojasok and Kay, 1990).

Earthworm activity can increase the water stability of soils through the production of casts (Lee, 1985) and by excreting materials from their bodies (Piearce, 1981). Earthworms can affect infiltration, water transport, and plant root development by creating macropores. Increased earthworm activity has therefore been suggested as an indicator of soil quality (Berry and Karlen, 1993).

Microbial biomass, respiration, and ergosterol concentrations are biological measurements that have been suggested as indicators for assessing long-term soil and crop management effects on soil quality (Karlen et al., 1992). Periodic assessments of soil-test properties have also been suggested as essential for evaluating the chemical aspects of soil quality (Arshad and Coen, 1992; Karlen et al., 1992). These may be especially important when no-till practices are used, because increased concentrations of nutrients, organic matter and hydrogen ions (decreased pH) in surface soils (typically 50 mm), and significant stratification of P and K have been reported by several researchers (Erbach, 1982; Blevins et al., 1983).

1.2. Soil quality assessment

Assessing soil quality is difficult, because unlike water quality or air quality for which standards have been established primarily by legislation, soil quality assessments are purpose- and site-specific. Larson and Pierce (1991) proposed five soil quality attributes and suggested that the combined physical, chemical, and biological properties of a soil enable it to perform three functions. These are to: (1) provide a medium for plant growth; (2) regulate and partition water flow through the environment; and (3) serve as an environmental filter. They stated that soil quality describes how effectively soils:

(1) accept, hold, and release nutrients and other chemical constituents,
(2) accept, hold, and release water to plants, streams, and groundwater,

(3) promote and sustain root growth,
(4) maintain suitable soil biotic habitat, and
(5) respond to management and resist degradation.

Acton and Padbury (1993) proposed two critical soil functions, each representing major expectations placed on soils by farmers and agricultural or other resource managers. These were: (1) sustainable crop production or the capacity to produce crops; and (2) environmental sustainability or the capacity of the soil to serve as an environmental buffer, to accept, hold and release water to plants, streams, and groundwater, and to function as a source or sink for gaseous materials and the capacity to exchange those materials with the above-ground atmosphere.

Karlen and Stott (1994) proposed to evaluate soil quality by using several soil measurements to estimate how soil would function to accept and retain water, resist degredation, and support plant growth. The specific objectives of this study were: (1) to evaluate several biological, chemical, and physical indicators of soil quality using data collected from a long-term no-tillage experiment where crop residues were removed, doubled, or maintained each year for previous 10 years; and (2) to demonstrate how these indicators could be used to develop a soil quality index based on specific soil measurements that describe four soil functions: (a) accommodating water entry; (b) facilitating water transfer, adsorption, and delivery; (c) resisting degradation; and (d) supporting plant growth.

2. Materials and methods

This study was initiated in May 1991 at a site on the University of Wisconsin experimental farm near Lancaster, WI, USA. Samples were collected as a 10-year, no-tillage study, where corn stover had been maintained, removed to create residue-removal plots, or reapplied to create double-residue plots, was being terminated. Although referred to as "double-residue" plots, stover application was not exactly double because annual corn yields for the three treatments had not been equal. However, surface cover measurements immediately after planting averaged 9, 57, and 83% for 1981 through 1990. This suggests there had been substantial differences in carbon input for the three no-till treatments.

Predominant soils were Rozetta and Palsgrove silt loam. These soils have 0.6 to 1.5 m of loess over residuum that is derived from limestone and sandstone bedrock. Residuum thickness is variable across the 1.1 ha site. Slopes range from 10 to 13% and are predominantly north facing. The statistical design was a randomized complete block with four replications.

2.1. Physical properties

Near-surface soil samples for particle size and water-stable aggregate analysis were collected from a 15-cm by 15-cm by 5-cm volume with a garden trowel. The soil was hand sieved to obtain 1- to 4-mm aggregates which were stored at 4°C until water stability was measured using a modification of the method described by Kemper and Rosenau (1986). Water stability was also determined using a turbidimetric method (Williams et al., 1966; Jordahl, 1991). Particle size analysis of the <2 mm fraction was determined by the pipette method (Gee and Bauder, 1986). Porosity was calculated as described by Danielson and Sutherland (1986).

Penetration resistance was measured to a depth of 500 mm with a hand-operated penetrometer that had a 12.83 mm diameter, 30° cone with an area of 130 mm^2 (ASAE, 1991). Data are reported as the maximum force recorded as the cone passed through each 50-mm layer. Bulk density samples were collected with a tractor-mounted, auger-type powered core sampler similar to that described by Buchele (1961). Data were collected for each 50-mm layer. Volumetric water content was determined by drying the soil samples at 104°C.

A second soil sample, collected from the surface 80 mm of each plot, was divided into two subsamples. After air drying, one subsample was rotary sieved, while the other was dropped from a height of 2 m as described by Adam and Erbach (1992). Mechanical stability of soil aggregates was calculated by dividing the aggregate mean-weight-diameter after dropping the soil by the aggregate mean-weight-diameter before dropping. After sieving, the maximum force and energy needed to crush randomly selected individual soil aggregates having diameters of 9.5, 19, and 38 mm were determined with a Universal Testing Machine (Instron[2] Model 8501, Instron Corporation, Canton, MA, USA). Soil aggregates were placed on a platform supported by a load cell with a capacity of 22241 N. A hydraulically operated anvil was used to compress the aggregate against the load cell at a speed of 278 mm s^{-1} until the aggregate was crushed. The crushing energy for each aggregate was determined by integrating the area under the force by displacement curve using a numeric integration program written in *BASIC*. The maximum force for each aggregate was also determined with this software program.

Three 75- by 75-mm undisturbed surface soil cores were obtained from each plot. After trimming the surface, saturated hydraulic conductivity was determined on the cores using the constant head method (Klute and Dirksen, 1986). Water retention was measured using undisturbed soil cores at matric potentials of −0.5 to −40 kPa and for sieved samples for the −100 to −1500 kPa range using methods of Klute (1986).

2.2. Chemical properties

Samples were collected for soil-test analysis by using a 20-mm diameter hand probe. Eight cores per plot were collected and fractionated into seven depth increments (0 to 25-, 25 to 75-, 75 to 150-, 150 to 250-, 250 to 300-, 300 to 450-, and 450 to 600-mm). Samples were air-dried, crushed to pass a 2 mm sieve, and

[2]Mention of a trademark, proprietary product, or vendor does not constitue a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of the other products or vendors that may also be suitable.

analyzed for water pH, Bray P1, 1 M NH_4OAc exchangeable K, Ca, and Mg using standard soil-test procedures at the University of Wisconsin-Madison (Schulte et al., 1987). Cation exchange capacity (CEC) was estimated by summation. The NH_4-N and NO_3-N concentrations in a 2 M KCl extract were measured colorimetrically (Keeney and Nelson, 1982) using flow injection analysis technology from the Lachat Corporation (Lachat Instruments[2], Milwaukee, WI, USA). Method No. 12-107-06-2-A was used for NH_4-N and method No. 12-107-04-1-A was used for NO_3-N. After pulverizing a subsample from each plot for 5 min in a SPEX ball mill (SPEX Industries[2], Inc., Edison, NJ, USA), total carbon and nitrogen were measured by dry combustion using a Carlo-Erba NA1500 NCS analyzer (Haake Buchler Instruments[2], Inc., Patterson, NJ, USA). This procedure was used for both soil-test samples and the 1- to 4-mm aggregate samples.

2.3. Biological properties

Microbial biomass and respiration were determined by the methods of Jenkinson and Powlson (1976). Samples were obtained from the same location and depth as the aggregate stability samples. Bulk soil was forced through a 4-mm sieve, sealed, and kept at 4°C until analysis. Respiration and microbial biomass were determined by fumigation and incubation techniques, followed by measurements of CO_2 evolution at room temperature (25°C) from samples moistened to a soil matric potential of −33 kPa. Ergosterol, a component of fungal tissue that is an index of fungal biomass, was determined in each sample by extraction and HPLC (high pressure liquid chromatography) analysis (Grant and West, 1986).

Earthworm activity was evaluated by saturating the soil within a 0.25 m^2 frame for 20 min with a formaldehyde solution (6 ml of a 40% solution l^{-1}) as suggested by Edwards and Lofty (1977). Mature and immature earthworms coming to the surface within each frame were counted.

Statistical analyses were computed using PROC GLM (SAS Institute Inc., 1985). Fisher's protected LSD at the 0.05 level of significance was used to distinguish treatment differences.

2.4. Soil quality assessment

To demonstrate a method for evaluating soil quality, several chemical, physical, and biological indicators were included in a framework similar to that suggested by Karlen and Stott (1994). Four soil functions, (1) accommodating water entry, (2) facilitating water transfer and absorption, (3) resisting surface degradation, and (4) supporting plant growth, were selected as being important for this assessment.

The first function, accommodating water entry, was selected because to minimize soil erosion and to support plant growth, water falling on the soil surface must enter and not runoff. Infiltration measurements would be best for this assessment, but they were not made. Therefore, water stability of soil aggregates was chosen to reflect resistance of the surface soil to raindrop impact. Surface porosity was chosen as an indicator of the soil's capacity to accommodate water entry. Earthworm population was chosen as a surrogate for macropore number, assuming higher populations would create more burrows. Water transfer and absorption were identified as the second critical soil function because of the need to retain water for plant growth. Porosity in the upper 500 mm and total C (Hudson, 1994) in the upper 600 mm were chosen as indicators of capacity for water retention. Water stability of soil aggregates and the microbial processes which contribute to aggregate stability were chosen to reflect the ability of the surface soil to resist degradation. The ability to support plant growth was selected as the fourth critical function for our soil quality index. Soil measurements that could influence plant rooting, water availability, nutrient availability, and toxic factors were used to compute a value for this function.

Each biological, chemical, or physical parameter that was measured was normalized by assigning a value between 0 and 1 using standardized scoring functions (Wymore, 1993). The values chosen to normalize each soil quality measurement were derived from literature values for each parameter. An overall soil quality index was calculated for the upper 600 mm of these non-glaciated silt loam soils by summing weighted scores for each function shown in Eq. (1).

$$\text{SoilQuality}, Q = q_{\text{we}}(wt) + q_{\text{wt}}(wt) + q_{\text{rd}}(wt) + q_{\text{spg}}(wt) \tag{1}$$

where: q_{we} is Level 1 rating for accommodating water entry; q_{wt} is Level 1 rating for water transport and absorption; q_{rd} is Level 1 rating for resisting degradation; q_{spg} is Level 1 rating for supporting plant growth and wt is the weighting factor for each function.

We anticipate that the measurements and functions chosen to demonstrate how a soil quality index can be computed will be changed for other soils and other applications. However, our objective was to demonstrate a methodology for computing a soil quality index, rather than to provide a definitive answer with regard to the measurements or specific functions which should be included in a soil quality index.

3. Results and discussion

The biological, chemical, and physical indicators measured to evaluate the effects of various crop residue treatments in a 10-year, no-tillage experiment will be discussed first. Those which may be useful for computing a soil quality index are then used to demonstrate a procedure for such an assessment.

Seasonal (May through August) rainfall and corn grain yield, which averaged 8.1, 8.4, and 8.0 Mg ha^{-1} for removal, normal and double residue treatments, respectively, are presented in Table 1. The largest yield differences can be accounted for by seasonal differences in amount and distribution of rainfall. By assuming a 1:1 ratio between corn grain and stover yield (Larson et al., 1978), the approximate amount of crop residue transferred from removal to double residue plots can be estimated from this yield data. Exceptions for this would be in

Table 1
Seasonal (May through August) rainfall and yield[a] of corn grain at 155 g kg^{-1} water content as affected by 10-year crop residue treatments on non-glaciated silt loam soils near Lancaster, Wisconsin, USA

Year	Rainfall	Corn grain yield (Mg ha^{-1}) under crop residue treatment			Significance
		Removal	Normal	Double	
1981	492	9.7	9.8	7.7	$P \leq 0.003$ (1.0)
1982	464	9.6	8.3	8.9	$P \leq 0.165$ (NS)
1983	379	5.8	5.3	4.8	$P \leq 0.001$ (0.3)
1984	397	7.3	6.8	6.8	$P \leq 0.318$ (NS)
1985	298	7.2	7.5	7.6	$P \leq 0.645$ (NS)
1986	378	9.7	10.4	10.1	$P \leq 0.156$ (NS)
1987	544	10.3	11.1	10.7	$P \leq 0.139$ (NS)
1988	153	3.6	3.7	4.2	$P \leq 0.360$ (NS)
1989	316	8.0	10.8	10.7	$P \leq 0.004$ (1.4)
1990	462	9.7	10.2	8.6	$P \leq 0.184$ (NS)

[a]All treatments were planted with a no-till planter equipped with a 50 mm offset fluted coulter ahead of double disk furrow openers. Yields are mean values for four replicates. Numbers in brackets are $LSD_{(0.05)}$ values.

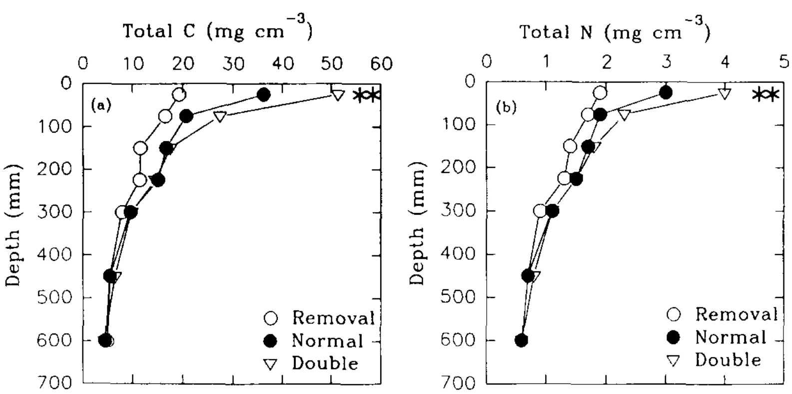


Fig. 1. Long-term crop residue removal, maintenance, or addition effects on total carbon and nitrogen within the upper 600 mm of a silt loam soil following 10 years of continuous corn. An ** indicates a significant difference among crop residue treatments at $P \leqslant 0.05$ at the depth specified.

1983 and 1988, when severe drought occurred, possibly reducing grain yield more than stover production.

The 10-year crop residue treatments had a significant effect on total carbon in the 0- to 25-mm and 25- to 75-mm depth increments (Fig. 1). Particle size analysis showed significantly higher clay content for the double-residue plots. This physical characteristic presumably reflected inherent variation across the 1.1 ha research site and some upward movement and deposition of clay from casting due to higher earthworm populations (Table 2), in the double residue plots. The

Table 2
Crop residue management effects on selected soil quality indicators following 10 years of continuous no-till corn production

Residue treatment	Wet aggregate stability		Total C in aggregates ($g\ kg^{-1}$)	Biomass[a] ($mg\ C\ kg^{-1}$ soil)	Respiration[b] ($mg\ C\ kg^{-1}$ soil)	Ergosterol ($\mu g\ g^{-1}$)	Earthworms ($No.\ m^{-2}$)
	Wet sieve (%)	Turbidity log (%T)[c]					
Removal	41.9	1.30	16	330	64	1.7	53
Normal	45.9	1.36	24	696	352	8.0	78
Double	60.0	1.53	40	1060	470	9.8	78
$LSD_{(0.05)}$	11.5	0.24	6	330	162	7.8	24

[a]Biomass = Microbial CO_2 evolved from soil fumigated with chloroform and reinoculated.
[b]Respiration = CO_2 evolved from untreated soil.
[c]logT = $\log_{10}$ of percent transmittance.

Table 3
Gravimetric water content, water-filled pore space, particle size analysis, and pH in the top 50 mm when sampled in May 1991 after 10-years of various crop residue management treatments

Residue treatment	Water content (%)	Water-filled pore space (%)	Clay (%)	Silt (%)	Sand (%)	pH
Removal	26.7	76.9	15.7	79.4	5.0	5.6
Normal	32.4	86.5	15.7	79.5	4.8	5.8
Double	37.8	88.0	18.1	77.7	5.0	6.0
$LSD_{(0.05)}$	8.8	NS	1.6	NS	NS	NS

higher clay content and increased soil carbon content from the crop residue additions (Hudson, 1994), presumably contributed to increased gravimetric water content in the top 50 mm (Table 3).

Water-filled pore space for all treatments at the time of sampling exceeded 60%, a level considered optimum for aerobic microbial activity and plant growth (Table 3). This indicates there was a high potential for denitrification, and it may have affected other biological indicators (Doran et al., 1990; Linn and Doran, 1984a,b).

Water stability of soil aggregates in the surface 50 mm (Table 2) showed that with wet sieving, macroaggregate stability for the double residue treatment was significantly greater than for normal and removal treatments. A turbidimetric method showed a similar, but statistically nonsignificant trend. Differences in water stability of soil aggregates were consistent with differences in total carbon and microbial activity in the aggregate samples; double and normal residue treatments had higher levels of both (Table 2). This was anticipated because maintaining or adding supplemental crop residues provides a food source for the soil microbial communities which produce binding agents that increase aggregate stability (Harris et al., 1966).

Higher fungal biomass may increase aggregate stability by enmeshing soil particles (Tisdall and Oades, 1982) and distributing binding substances throughout the soil (Aspiras et al., 1971). Significantly higher levels of ergosterol, a sterol related to fungal biomass (Eash et al., 1994), were found in plots receiving normal or double amounts of crop residue (Table 2). This suggests that long-term crop residue treatments were affecting fungal populations at this site. The sensitivity of ergosterol measurements to crop residue management treatments supports using this assay (Eash et al., 1994) as a soil quality indicator.

Total soil carbon measurements reflected the amount of crop residue that was returned to each treatment over the 10-year period. The soil microbial biomass, respiration, and earthworm populations paralleled total soil carbon differences. However, soil respiration and earthworm populations in double residue treatments were not significantly different from those in normal residue plots (Table 2).

Porosity, measured using another set of soil cores from the top 75 mm (Table 4), showed no significant crop residue treatment differences. Geometric mean values for saturated hydraulic conductivity were 1.5, 6.1, and 18.9 μm s^{-1} for removal, normal, and double residue treatments, respectively. The differences, although large, were not statistically significant and presumably reflect the difficulty in quantifying hydraulic conductivity effects of long-term tillage or crop residue management practices with small soil cores.

Plant available water in the top 75 mm, defined as the difference in volumetric water content between soil matric potentials of -9.8 and -1500 kPa, was significantly different (Table 4) between the removal and double residue treatments. These changes paralleled changes in total soil carbon (organic matter), thus supporting arguments by Hudson (1994) that soil organic matter is an important determinant of available water capacity. Volumetric water content (θ) at soil

Table 4
Crop residue management effects on porosity, plant available water, and volumetric water content in the surface 75 mm following 10 years of continuous no-till corn production

Residue treatment	Porosity (%)	Plant available water (PAW)[a] (%)	Volumetric water content (θ) (cm^3 cm^{-3}) at selected matric potentials (kPa)				
			-0.5	-1.3	-9.8	-100	-1500
Removal	43.5	23.2	0.374	0.371	0.359	0.329	0.127
Normal	44.2	24.5	0.385	0.381	0.370	0.324	0.125
Double	45.7	25.8	0.400	0.396	0.380	0.316	0.122
$LSD_{(0.05)}$	NS	1.6	0.019	0.018	0.013	NS	NS

[a]Plant available water was calculated as volumetric water content at $\psi = -9.8$ kPa minus volumetric water content at $\psi = -1500$ kPa.

Table 5
10 year crop residue management effects on soil bulk density

Sample depth (mm)	Removal (Mg m^{-3})	Normal (Mg m^{-3})	Double (Mg m^{-3})	Average (Mg m^{-3})
0–50	1.38	1.33	1.24	1.32
50–100	1.50	1.57	1.55	1.54
100–150	1.46	1.53	1.53	1.51
150–200	1.48	1.52	1.49	1.49
200–250	1.54	1.53	1.52	1.53
250–300	1.48	1.52	1.48	1.50
300–350	1.52	1.52	1.50	1.51
350–400	1.53	1.54	1.44	1.50
400–450	1.56	1.50	1.55	1.54
450–500	1.56	1.63	1.44	1.54
$LSD_{(0.05)}$		NS		0.06

matric potentials of -0.5, -1.3 and -9.8 kPa showed significant differences, similar to plant available water measurements. The removal treatment had the lowest porosity, lowest θ at $\Psi = -9.8$ kPa, and the highest θ at $\Psi = -1500$ kPa. Therefore, that treatment had the lowest plant available water content.

Penetration resistance to a depth of 500 mm, showed no statistically significant effects owing to crop residue management treatments. Means by depth (data not presented) were significantly different at $P \leqslant 0.07$ when averaged across residue management treatments. Soil bulk density was not affected by crop residue management treatments (Table 5), but differences between depth means were significant ($P \leqslant 0.05$).

Mean weight diameter before dropping soil aggregates from a height of 2 m ranged from 38 to 50 mm, while after dropping the mean weight diameter ranged from 22 to 43 mm. There were no significant differences among residue management treatments. When averaged across aggregate sizes, the maximum force and energy required to crush soil aggregates with diameters of 9.5, 19, or 38 mm before dropping ranged from 71 to 82 N and from 0.11 to 0.19 J, respectively. There were no significant differences owing to crop residue treatments. The maximum force required to crush the three aggregate sizes, when averaged across crop residue management treatments, was 40, 69, and 120 N, respectively. These values were significantly different with an $LSD_{(0.05)}$ value of 37. After dropping, maximum force and energy values ranged from 49 to 135 N and 0.07 to 0.24 J when averaged across aggregate sizes. Similarly, when averaged across crop residue management treatments, the values ranged from 40 to 148 N and from 0.09 to 0.22 J. Crop residue and aggregate size effects were statistically significant ($P \leqslant 0.05$), but the data were highly variable. There were no significant interactions.

3.1. Soil chemical characteristics

Arshad and Coen (1992) stated that high quality soil must have a readily available supply of plant nutrients. Total C and N measurements among the crop residue management treatments were significantly different for the 0 to 25-mm depth increments (Fig. 1). Total N concentration in the 0 to 25-mm increment was more than twice as high in the double residue treatment as in the removal treatment. Doubling the amount of crop residue on the surface for 10 years increased total soil nitrogen by approximately 30% compared with the normal residue treatment. Differences at other depths were not significant.

The ammonium concentrations (Fig. 2(a)) showed no significant differences among crop residue management treatments. The nitrate concentrations (Fig. 2(b)), although transient in these soils, showed significant differences ($P\leqslant 0.05$) in the 0 to 25- and 600 to 900-mm increments when sampled. The concentrations at the 300 to 600-mm increments were significantly different at $P\leqslant 0.10$. Samples from the residue removal treatment had the lowest nitrate concentrations in the 0 to 25- and 25 to 75-mm increments, but the highest in each increment below 225 mm. Perhaps the significantly lower carbon levels (Fig. 1) in the top two increments resulted in less N immobilization in microbial biomass, and therefore increased leaching to the lower depths.

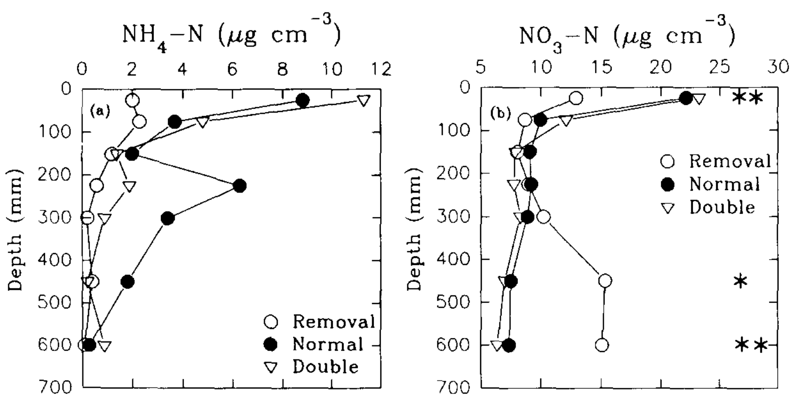
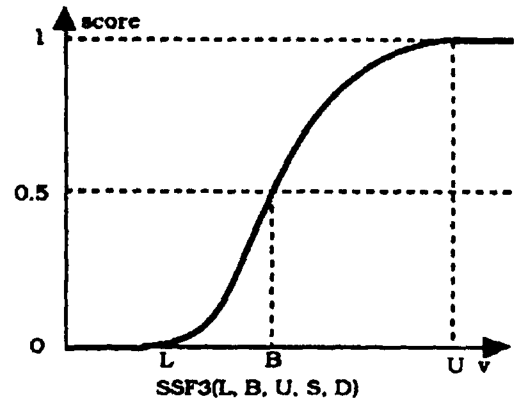


Fig. 2. Long-term crop residue removal, maintenance, or addition effects on NH_4-N and NO_3-N within the upper 600 mm of a silt loam soil following 10 years of continuous corn. An ** indicates a significant difference among crop residue treatments at $P\leqslant 0.05$ at the depth specified, while an * indicates a significant difference at $P\leqslant 0.10$ at the depth specified.

Fig. 3. Standard scoring functions (SSF) showing a 'more is better' (top), 'optimum' (middle), or 'less is better' relationship. Abbreviations beneath each curve are defined as follows: L – lower threshold, values at or below this receive a score of 0; B – baseline, values which receive a score of 0.5 and are generally regarded as minimum target values; U – upper threshold, values at and above this level receive a score of 1.0; O – optimum level, the value is given a score of 1.0 if the desired relationship is bell-shaped; B1 – lower baseline (0.5 value) for bell-shaped response curves; B2 – upper baseline (0.5 value) for bell-shaped response curves; D – domain or the range of values across which the scoring function is computed.


score
1
0.5
0
L
B
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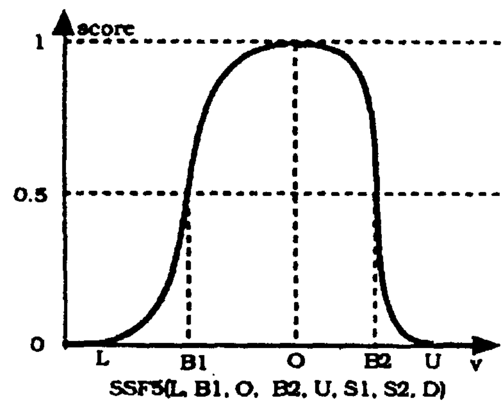
v
SSF3(L, B, U, S, D)


score
1
0.5
0
L
B1
O
B2
U
v
SSF5(L, B1, O, B2, U, S1, S2, D)

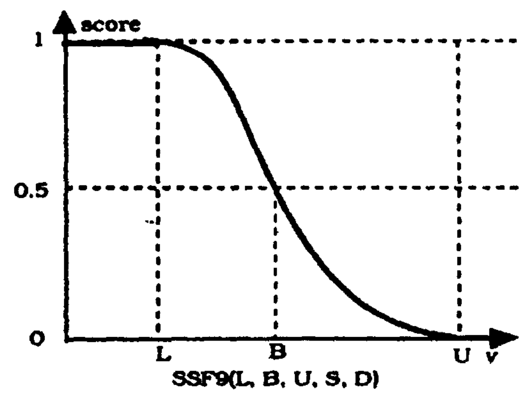

score
1
0.5
0
L
B
U
v
SSF9(L, B, U, S, D)

Table 6
Parameters used to develop a soil quality for evaluating crop residue effects

Parameter	SSF[a]	LT[a]	BL[a]	UT[a]	LB[a]	OL[a]	UB[a]	Soil functions affected	Reference
Aggregation (%)	3	30	45	60	–	–	–	Water entry and resistance to degradation	Wilson and Browning (1945)
Surface 75 mm porosity (%)	5	20	–	80	40	50	60	Water and air entry into soil	Hillel (1971)
Upper 500 mm porosity (%)	5	20	–	80	40	50	60	Water and air movement in root zone	Hillel (1971)
Surface 75 mm bulk density ($Mg\ m^{-3}$)	9	1.3	1.8	2.1	–	–	–	Water entry and seed germination	Singh et al (1992)
Upper 500 mm bulk density ($Mg\ m^{-3}$)	9	1.3	1.8	2.1	–	–	–	Plant root growth, water and nutrient uptake	Singh et al. (1992)
Micriobial biomass ($mg\ C\ kg^{-1}$)	3	75	350	700	–	–	–	Resistance to degradation and plant growth through nutrient cycling	Linn and Doran (1984a)
Respiration ($mg\ C\ kg^{-1}$)	3	0.5	3.0	8.0	–	–	–	Resistance to degradation and plant growth through nutrient cycling	Linn and Doran (1984a)
Ergosterol ($\mu g\ g^{-1}$)	3	75	350	700	–	–	–	Resistance to degradation and plant growth through nutrient cycling	Eash (1993)
Earthworm population (no. m^{-2})	3	25	75	125	–	–	–	Water entry, transfer, plant growth by forming potential rooting channels	Edwards and Lofty (1977)
Soil pH	5	4.5	–	9.0	5.3	6.5	7.5	Supporting plant growth	Arshad and Coen (1992)
Total C in surface 75 (mm ($mg\ cm^{-3}$)	3	15	30	50	–	–	–	Resist degradation, nutrient cycling	Tisdall and Oades (1982)
Total C in upper 500 mm ($mg\ cm^{-3}$)	3	6	12	20	–	–	–	Nutrient cycling, water retention	Hudson (1994)
Total N in surface 75 mm ($mg\ cm^{-3}$)	3	1.5	3.0	5.0	–	–	–	Nutrient cycling, support microbial activity	–
Total N in upper 500 mm ($mg\ cm^{-3}$)	3	0.6	1.2	2.0	–	–	–	Nutrient cycling, support plant growth	–
Cation exchange capacity ($cmol\ kg^{-1}$)	3	5	10	15	–	–	–	Supporting plant growth	–
Plant available water (volumetric %)	3	10	20	30	–	–	–	Supporting plant growth	–
Water-filled pore space (%)	5	15	–	105	30	60	90	Microbial processes	Linn and Doran (1984b)

[a]Column abbreviations refer to various parts of the standard scoring functions (SSF) shown in Fig. 3.
Column abbreviations are defined as follows: LT–lower threshold, values at or below this receive a score of 0; BL–baseline, values which receive a score of 0.5 and are generally regarded as minimum target values; UT–upper threshold, values at and above this level receive a score of 1.0; OL–optimum level, the value given a score of 1.0 if the desired relationship is bell-shaped; LB–lower baseline (0.5 value) for bell-shaped response curves; UB–upper baseline (0.5 value) for bell-shaped response curves.

Soil pH, P, K, Ca, and Mg concentrations were also measured, but in general, treatment differences were not statistically significant (data not shown). Cation exchange capacity (CEC) in the 0 to 25-mm increment for the double residue treatment (12.8 cmol kg^{-1}) was significantly higher ($P \leq 0.05$) than in either the normal or removal treatments which averaged 10.3 and 9.8 cmol kg^{-1}, respectively. Cation exchange capacity was also the highest in the double residue plot for the 25 to 75 mm depth (10.3 cmol kg^{-1}), but this value was significantly greater only compared with the normal treatment, which averaged 9 cmol kg^{-1}. Long-term supplemental crop residue additions increased soil carbon content (Fig. 1) and presumably contributed to some of the increased cation exchange capacity. However, the clay content of samples from the double residue treatments was also higher (Table 3) and this too may have increased the CEC in those plots.

3.2. Soil quality assessment

Effects of the 10-year crop residue management treatments on upper profile (0 to 600 mm) soil quality at the time of sampling were evaluated by computing a soil quality index based on four soil functions. These were: (1) accommodating water entry; (2) retaining and supplying water to plants; (3) resisting degradation; and (4) supporting plant growth.

Biological, chemical, and physical measurements were normalized on a scale from 0 to 1 using one of the standard scoring functions (SSFx) developed for systems engineering (Wymore, 1993) and shown in Fig. 3. The type of scoring function (x) used to normalize each measurement is presented in Table 6. After deciding the shape of the anticipated response, (i.e. if a measurement should be normalized using a 'more is better' ($x=3$), 'optimum' ($x=5$), or 'less is better' ($x=9$) relationship), baseline and threshold values (Table 6) were chosen based on literature values or experience with these soils. A brief rationale and references from which the baseline and threshold values were obtained for each measurement used in the soil quality index are presented in Table 6.

The proposed conceptual model for computing a soil quality index (Table 7) utilizes systems engineering concepts by identifying several factors affecting each soil function. With respect to accommodating water entry (Function 1), water stability of soil aggregates was assigned the highest priority (0.60), followed by earthworm number, which served as a surrogate for macropores, and surface porosity (0.20). Soil water transfer and absorption (Function 2) were assumed to be affected most by porosity (0.60), followed by earthworm number (as a surrogate for macroporosity) and carbon content (0.20). Resistance to degradation (Function 3) was assumed to be affected by current soil surface conditions (i.e. water stability of soil aggregates (0.60)) and changes that would be related to microbial processes (0.40). Measurements influencing microbial processes and their suggested relative importance are presented in Table 7. The ability to support plant growth (Function 4) was assumed to be influenced by factors affecting plant rooting, water retention, nutrient cycling, and possible toxic factors (i.e. soil pH for these soils).

Table 7
Soil quality functions and indicators related to seedbed quality as affected by various crop residue management treatments on silt loam soils in southwestern Wisconsin

Function	Weight	Indicator					
		Level I	Weight	Level II	Weight	Level III	Weight
Accomodate water entry	0.20	Aggregate stability	0.60				
		Surface 75 mm porosity	0.20				
		Earthworms	0.20				
Facilitate water transfer and absorption	0.20	Upper 500 mm porosity	0.60				
		Upper 600 mm total carbon	0.20				
		Earthworms	0.20				
Resist degradation	0.20	Aggregate stability	0.60				
		Microbial processes	0.40	Microbial biomass	0.30		
				Respiration	0.30		
				Ergosterol	0.20		
				Surface 75 mm total carbon	0.10		
				Surface 75 mm total nitrogen	0.10		
Sustain plant growth	0.40	Rooting depth	0.30	Surface 75 mm bulk density	0.20		
				Earthworms	0.10		
				Upper 500 mm bulk density	0.50		
				Plant available water (PAW)	0.20		
		Water relations	0.30	PAW	0.25		
				Surface 75 mm porosity	0.25		
				Upper 500 mm porosity	0.40		
				Upper 600 mm total carbon	0.10		
		Nutrient relations	0.30	pH	0.30		
				CEC	0.20		
				Upper 600 mm total nitrogen	0.10		
				Upper 600 mm total carbon	0.10		
				Nutrient cycling	0.30	Microbial biomass	0.10
						Respiration	0.10
						WFPS	0.25
						Ergosterol	0.05
						Surface 75 mm total N	0.25
						Surface 75 mm total C	0.25
		Chemical barriers (pH or acidity)	0.10				

After normalizing or scoring each measurement used for the proposed soil quality index, scores were multiplied by the appropriate weighting factor (Table 7). The products were then summed to give a weighted value. For factors such as nutrient relationships, weighted values for nutrient cycling (level III) were computed and then used as the 'score' for that factor at level II. Similarly, all level II factors (pH, CEC, total N, total C, and nutrient cycling) were then multiplied by their respective weighting factor so that products could be summed to give weighted scores for each level I factor. Weighted scores for each function were then summed to give an overall soil quality index (Eq. (1)).

The parameters selected for inclusion in this soil quality index will undoubtedly change and have different priorities or weights assigned as the concept of computing a soil quality index is refined. However, our objectives for this study were to demonstrate a potential framework for computing a soil quality index and to determine if such an index was sensitive to the long-term crop residue treatments. Calculations using the proposed methodology result in surface (0 to 600 mm) soil quality ratings of 0.45, 0.68, and 0.86 for the removal, normal, and double residue no-tillage treatments. This suggests that over the 10-year period, retaining or adding crop residues improved soil quality in this no-tillage continuous corn program. We envision that a soil quality index developed using this type of framework could be used periodically to determine if soil quality was degrading, improving, or remaining constant.

4. Summary and conclusions

This study demonstrates that maintaining or adding crop residue, even in the absence of tillage, improves several biological, chemical, and physical characteristics of silt loam soils. These improvements presumably enable the soil to resist water and wind erosion, to retain more water, and to retain essential plant nutrients. These findings should encourage adoption of practices that maintain or even increase the amount of crop residue that is returned each year.

We have also demonstrated how various soil biological, chemical, and physical measurements can be combined to assess soil quality relative in the upper 600 mm of the soil profile. The overall soil quality assessment quantifies the benefits of maintaining or adding crop residues on non-glaciated silt loam soils such as the Palsgrove and Rozetta. Our assessment, although developed specifically for non-glaciated silt loam soils also demonstrates how a framework, based on specific soil measurements that describe selected soil functions, can be developed and used to quantitatively describe and evaluate soil quality. We conclude that this approach can easily be adapted to other soils and types of evaluation.

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